IMPROVING THE FUNDAMENTAL UNDERSTANDING OF REGIONAL SEISMIC SIGNAL PROCESSING WITH A UNIQUE WESTERN UNITED STATES DATASET

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ABSTRACT

This project has built a unique historic database of regional distance nuclear explosion, earthquake, and mine-related digital broadband seismograms for the western United States (US). The emphasis is on data from Lawrence Livermore National Laboratory (LLNL)-managed stations MNA, ELK, KNB and LAC that recorded many nuclear tests and nearby earthquakes in broadband digital form since 1980, along with a small number of earlier events that were digitized from tapes. Through the generous cooperation of Sandia National Laboratories (SNL) we have also included waveforms from their Leo Brady network (BMN, DWN, LDS, NEL,TON). In addition we include data from other open broadband stations in the western US with long operating histories and/or ties to the International Monitoring System (e.g. PFO, YKA, CMB, NEW, DUG, ANMO, TUC). These waveforms are associated with a reconciled catalog of events and station response information to facilitate analysis. The goal is to create a high-quality database that can be used in the future to analyze fundamental regional monitoring issues such as detection, location, magnitude, and discrimination.

In the first stage of the project, we collected six different regional network catalogs from the University of Nevada, Reno, to provide accurate independent location information for events on the Nevada Test Site and in the surrounding region. We have used National Nuclear Security Administration (NNSA)-developed software to reconcile these catalogs with each other and to incorporate them into a set of larger continental scale (CNSS, see http://www.cnss.org; USGS mining catalog compiled by Jim Dewey) and global scale (PDE, REB, and ISC) catalogs. Finally, we incorporate the best catalogs of NTS nuclear event locations and source properties (Springer et al. 2002). The result is a single catalog of preferred origins, source information, and station information. Concurrently, we collected continuous seismic data from open stations and recovered and reformatted old event segmented data from the LLNL and SNL managed stations for past nuclear tests and earthquakes. We then used the preferred origin catalog to extract waveforms from continuous data and associate event segmented waveforms within the database. The result is a well-organized regional western US dataset with hundreds of nuclear tests, thousands of mining explosions and hundreds of thousands of earthquakes.

In the second stage of the project we have chosen a subset of approximately 125 events that are well located and cover a range of magnitudes, source types, and locations. Ms. Flori Ryall, an experienced seismic analyst is reviewing this dataset. She is picking all arrival onsets with quantitative uncertainties and making note of data problems (timing errors, glitches, dropouts) and issues. The resulting arrivals and comments will then be loaded into the database for future researcher use. During the summer of 2003 we will be carrying out some analysis and quality control on this subset. It is anticipated that this set of consistently picked, independently located data will provide an effective test set for regional sparse station location algorithms. In addition, because the set will include nuclear tests, earthquakes, and mine-related events, each with related source parameters, it will provide a valuable test set for regional discrimination and magnitude estimation as well. A final relational database of these approximately 125 events in the high quality subset will be put onto a CD-ROM and distributed for other researchers to use in benchmarking regional algorithms after the conclusion of the project.

OBJECTIVE

The objective of this project is to build a historic western U.S. database of regional distance nuclear explosion, earthquake, and mine-related digital broadband seismograms with their associated parameters (origin's times and location, instrument response, etc.). Although the original title of the project remains unchanged, its scope has been reduced to match the level of funding awarded. Therefore we focus on a subset of this data to undergo careful quality control, to provide independent regional network ground-truth location and to perform quantitative regional phase picking. This subset will be released as a CD-ROM at the conclusion of the project and provide source type and location ground-truth data for monitoring researchers to make use of in benchmarking regional algorithms.

RESEARCH ACCOMPLISHED

Seismic nuclear monitoring research is data driven. The number of digital seismic records of underground nuclear tests at regional distances is quite restricted both in number and geographical location. Consequently, the finite number of existing regional nuclear test records are a unique resource that needs to be thoroughly exploited to create the best verification system possible. We believe that this exploitation is incomplete for the extensive Nevada Test Site (NTS) nuclear explosion records. Therefore in this project our goal is to build the largest, most complete, and best-documented database of explosions, earthquakes, mine blasts and mine tremors in the Western U.S. Once completed we believe this database will provide a well-organized and highly efficient way to conduct fundamental monitoring research on regional seismic event detection, location and identification.

Building a Comprehensive Western U.S. Database

The process of building this new database involves a series of steps, which include:

1. Collecting local, regional and global seismicity catalogs from the NTS and the western U.S.
2. Reconciling catalogs into a single table of events with preferred origin information
3. Compiling event parameter information (e.g. yield, material properties, focal mechanisms, etc.)
4. Collecting continuous data from selected stations
5. Compiling station site and instrument response information
6. Extracting event waveforms from continuous data and loading into database with ties to the reconciled catalog
7. Selecting a high quality data subset to analyze
8. Quantitatively analyzing the data subset and loading timing picks and uncertainties into database
9. Distributing data subset and maintaining database for use in nuclear explosion monitoring research

At the time of this writing we have completed steps 1-7 and are working on steps 8-9. Here we briefly describe the research accomplished on this project so far.

We have attempted to obtain as complete of a list, as possible, of catalogs in the vicinity of the NTS and the western U.S. Springer et al. (2002) have compiled the most complete listing of dates, locations and working point parameters (e.g. depth, working point density, velocity, gas porosity) for U.S. underground nuclear tests. These parameters affect seismic frequency content and discriminants (e.g. Walter et al., 1995). The University of Nevada Reno (UNR) runs regional seismic networks in southern and northern Nevada that provide the most complete and accurate lists of earthquakes for this region. We have worked with UNR to obtain, the most complete a set of catalogs for the state of Nevada. We believe these local networks can be used to obtain independent high quality ground-truth location and depth information.

In addition to Nevada and NTS catalogs, we have also collected a number of regional and global scale catalogs. A U.S. seismicity catalog is compiled regularly by the University of California at Berkeley from most of the regional seismic network operator's catalogs in the country as part of the Council of National Seismic Stations (see http://www.cnss.org). Although this catalog contains a very large number of events, it does not capture all of the events in the local UNR catalogs listed above. We have also collected the United States Geological Survey (USGS) mine explosion listing that is compiled by Jim Dewey. Finally, we include the standard global catalogs from the

USGS Preliminary Determination of Epicenters (PDE), the International Seismological Commission (ISC) and the International Monitoring System (IMS) Reviewed Event Bulletin(REB).

We have gained much experience in building large reconciled databases over the past several years (see O'Boyle et al, this volume) and we make full use of these tools and procedures in this project. We assign each of these catalogs a rank order for reconciliation. The catalogs are then parsed, and locations and origin times are compared. Events in common are assigned to one unique event identification number and the highest-ranking catalog's origin information then becomes the preferred one. The other origin information is retained as well. In this way we build up a single listing of events that can be used to extract waveforms from continuous data or tie to event-segmented data. For a more complete discussion of the catalog reconciliation process see O'Boyle et al. (this volume).

Table 1. Seismicity Catalogs Collected, Parsed and Reconciled for this Project

Date Range	Source Types	Catalog Name	Comments and References
1946-1992	Nuclear tests	Springer catalog	Below surface tests, Springer et al (2002)
1978-2000	Earthquakes	UNR_SGB_merged	Covers Southern Great Basin (SGB) only
1992-2000	Earthquakes	UNR_SGB_relocated	Covers Southern Great Basin (SGB) only. Smith et al. (2002)
1868-2000	Earthquakes	YMP_PSHA	Yucca Mountain Project (YMP) Probability of Seismic Hazard Assessment (contains a composite of many catalogs within 300 km of YM)
1978-1999	Earthquakes	UNR_NN_consolidated	Covers Northern Nevada (NN) area only
2000-2001	Earthquakes	UNR_2000-2001	University of Nevada Reno networks catalog
2002-2003	Earthquakes	UNR_2002present	University of Nevada Reno networks catalog
1850-1998	Earthquakes	Nevada historic catalog	Compiled by Depolo and Depolo (1999)
1898-2002	Earthquakes	CNSS	Council of National Seismic Stations - a partially reconciled catalog of western US seismicity compiled by UC Berkeley
1920-2002	Earthquakes, explosion and mine tremors	USGS Monthly PDE	Preliminary Determination of Epicenters (PDE)
1964-1999	Earthquakes	ISC	International Seismological Commission (ISC)
1995-2000	Earthquakes	IMS REB	Comprehensive nuclear-Test-Ban Treaty International Monitoring System (IMS) Reviewed Event Bulletin (REB)
1997-2003	Mine Blasts	USGS Dewey catalog	A catalog of mining explosions compiled by Jim Dewey at the U.S. Geological Survey

A major emphasis of this project is on regional seismic waveforms from the four LLNL seismic stations operated by the Livermore NTS Network (LNN). These stations, all digital since about 1980, have recorded more than 120 underground nuclear tests during that time. In addition, there are a number of waveforms that were digitized from analog records that are of a more uncertain quality. We have identified the LNN waveforms from approximately 300 nuclear tests to review for quality control and to include in the database. Another large database of regional nuclear seismic waveforms was recorded on the Leo Brady Seismic Network (stations BMN, DAC, LDS, MVU, TPH) that is operated by Sandia National Laboratories (Lee, 2001). Through the generous cooperation of Sandia personnel we have included this dataset in the database as well. Both of these networks have recorded hundreds of

regional earthquakes, many in close proximity to prior nuclear tests and make an excellent dataset for studying the physical basis of regional seismic discrimination.

In addition to the national laboratory-managed networks, we have collected data from other broadband open seismic stations that are archived by the Incorporated Research Institutes for Seismology Data Management Center (IRIS DMC.) We have selected a subset of these stations with emphasis on stations that have long operating histories, stations that are part of the IMS network and stations that are spread throughout the western U.S. Table 2 below gives a list of the stations for which we have collected data to be included in the database.

Table 2. Seismic Station Data Retrieved for Event Waveform Extraction to Database

Data Type and Period	Station code	Location and comments
Continuous 1988-2001	PFO	Pinion Flat, California (IMS Auxiliary station)
Continuous 1989-2001	COR	Corvalis, Oregon
Continuous 1989-2001	ANMO	Albuquerque, New Mexico (IMS Auxiliary station)
Continuous 1992-2001	CMB	Columbia, California
Continuous 1992-2001	TUC	Tucson, Arizona
Continuous 1993-2001	YBH	Yreka, California (IMS Auxiliary station)
Continuous 1997-2001	DUG	Dugway, Utah
Continuous 1997-2001	TPNV	Topapah Springs, Nevada
Continuous 1997-2001	NEW	Newport, Washington (IMS Auxiliary station)
Continuous 1992-2002 Event segments 1968-1992	ELK	Elko, Nevada (IMS Auxiliary station)
Continuous 1992-2002 Event segments 1968-1992	KNB	Kanab, Utah
Continuous 1992-2002 Event segments 1968-1992	MNV	Mina, Nevada (IMS Primary array element)
Continuous 1992-1998 Event segments 1968-1992	LAC	Landers, California (closed in 1999)
Event segments	BMN	Battle Mountain, Nevada
Event segments	DAC	Darwin, California
Event segments	LDS	Leeds, Utah
Event segments	TPH	Tonopah, Nevada
Event segments	MVU	Marysvale, Utah

Additional event-segmented data that was collected over a limited time (for other projects) has been included in this database (e.g. WUAZ, SRU, GSC, ISA, NEE, NVAR, PDAR) for long-term storage and analysis.

In Figure 1 we show a map of the region with the locations of stations (Table 2) for which we are archiving seismic data and the locations of the reconciled events from 1997 to the middle of 2002. We selected 1997 as the starting point for this plot because that is when the Dewey catalog of mine seismicity starts. The reconciled catalog goes back to 1852. Figure 1 shows more than 8000 earthquakes and 1600 mining events (mainly explosions) in our reconciled catalog with magnitudes (mb, Mw or ML) greater than or equal to 2.5. The catalog does include events of all magnitudes and in some locations where the UNR network is dense there are magnitudes of -1 or smaller.

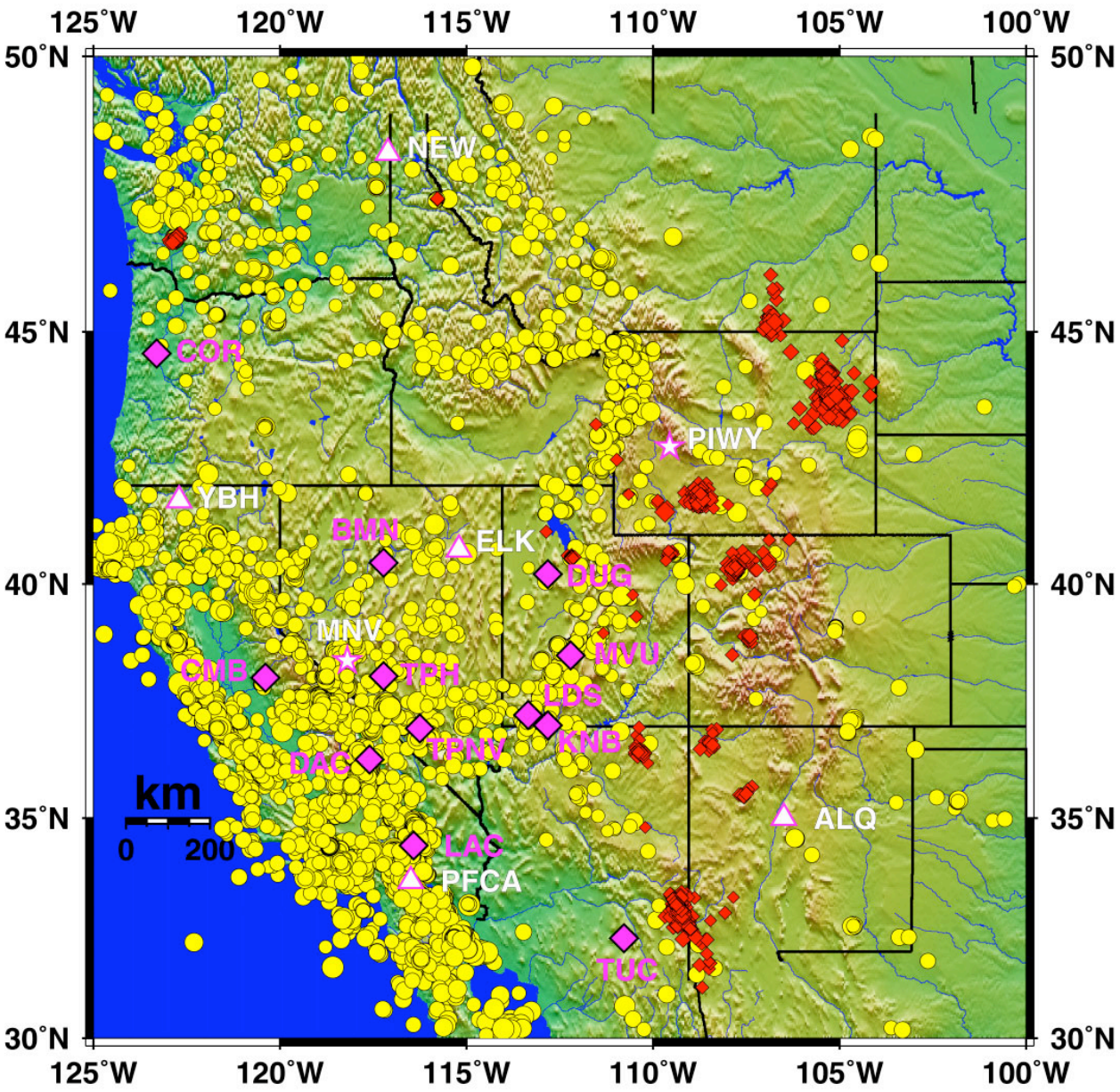

Figure 1. A shaded relief map showing the locations of seismic stations and select events in this project. Stations are listed in Table 2 and the events are drawn from a reconciled composite catalog created from the catalogs listed in Table 1. IMS primary stations are plotted as white stars. IMS auxiliary stations are plotted as white triangles and other broadband stations are plotted as pink diamonds. Seismic stations are labeled by name. Earthquakes are plotted as yellow circles and mine seismicity as small red diamonds. Seismic event symbols are scaled by magnitude.

Overall the western U. S. database contains 9.5 million waveforms from 360,000 events and occupies 1.2 terabytes of storage space in the LLNL Seismic Research Data Base (SRDB) (O'Boyle et al., this volume). A database of this size represents a significant resource for nuclear explosion monitoring research, but is impractical to distribute and will be maintained at LLNL. For both quality control purposes and to make a useful subset of this database for the broader research community, we are developing a high quality subset of this data for distribution on CD-ROM at the conclusion of this project.

High Quality Data Subset

For this subset we have selected approximately 125 events for detailed analysis. These events include 74 NTS controlled nuclear explosions, the 1993 NPE (Non Proliferation Experiment) chemical kiloton explosion, 30 earthquakes located on or near NTS, 20 earthquakes located in the broader western U.S., and 10 mining explosions from two mining districts in Arizona. This dataset is being analyzed by Ms. Flori Ryall, a seismic analyst with decades of experience. Flori will pick all arrival onsets with quality designations that can be mapped to quantitative uncertainties and make note of data problems (timing errors, glitches, dropouts) and other issues. These picks will then be loaded back into the database for researcher use. This effort has been ongoing this year and several thousand picks have been made so far. We anticipate completion of this task by the end of summer.

As an example of these picks we show the Pn, Pg and Lg picks with a high quality designation from the 74 NTS explosions shown in Figure 2. These events have a very precise location and timing (GT0) giving an excellent set of travel time curves for the basin and range. In the lower part of this figure we focus on the reduced Pn travel times for each station. First we note that none of the stations have good picks for all 74 events, due to station down time. Because nuclear testing at NTS ended in 1992, many of the open station networks (shown in red) have a very limited number of picks. In contrast, the two regional networks maintained by LLNL and SNL have a very large number of picks for the nuclear tests making them quite valuable for regional research. Looking at quality control, we note that a number of NTS events at the LLNL stations during the 1982-1983 time frame (Atrisco, Borrego) appear to have network clock problems of a couple of seconds. There also appear to be both network and individual station clock errors ranging from a couple seconds to tenths of seconds. Clock errors that are less than one second are very difficult to distinguish from picking errors. Despite these events with clock errors the dataset is large enough that after removing outliers we are able to obtain a very tight fit to linear travel time curves.

One goal for this high quality subset is to choose events with excellent ground-truth hypocenters from the regional networks for use in location research. The NTS explosions are clearly the best dataset for this purpose. These data and their picks are currently being used in relative regional relocation research (see location paper by Myers et al., this volume). For the earthquakes on or near the NTS we obtained the local UNR network data and re-picked these to allow high-quality local network locations to provide ground-truth independent of that based on the regional stations. We believe the high quality picks at local, near and far regional distances when combined with the independent ground truth will be useful in testing and benchmarking sparse station location algorithms.

We have also selected the high quality dataset with an eye towards discrimination research. Therefore, in addition to excellent ground truth locations, we also chose events that have well documented source properties. For explosions this means working point source medium properties such as density, P-velocity, and gas porosity. We have selected explosions that span a wide range of these properties. There are also a small number of explosions with announced yields and we use these events to facilitate yield estimation research. Finally we try to span the full range of magnitudes and depths to include a few of the larger explosions that were conducted prior to the 150 kt Threshold Test Ban Treaty of 1974. For earthquakes we want to select events that cover a range of magnitudes, depths and locations in the western U.S. For this reason we have picked events with some aftershock sequences (e.g. 1992 Little Skull Mountain, 1999 Scotty's Junction, 1999 Hector Mine, 1993 Eureka Valley, 1993 Cataract Creek). We also want focal mechanism information for as many of the earthquakes as possible. The impact of variations in focal mechanism and depth on regional discriminants are the subjects of current research (e.g. Zhang et al., 2002).

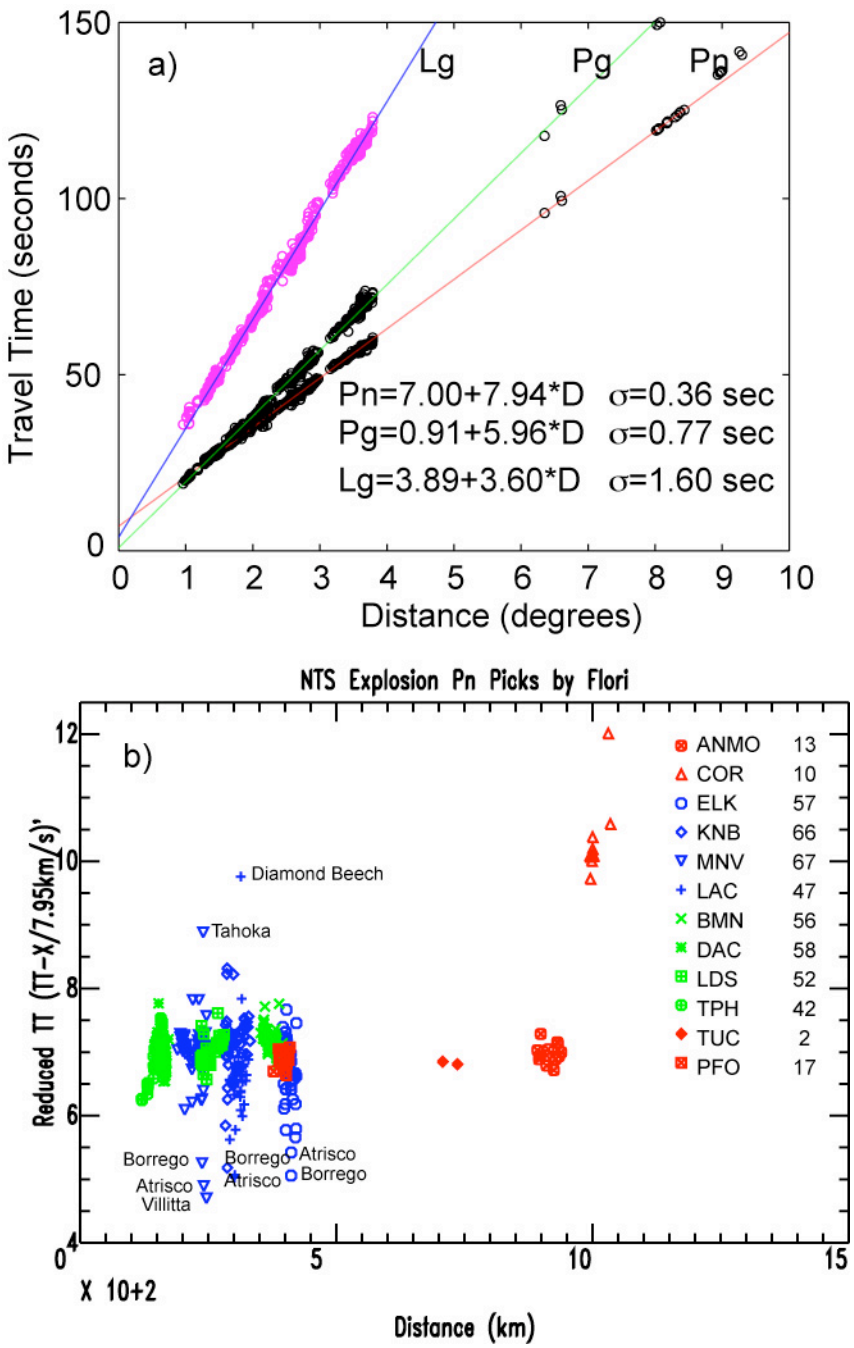

Figure 2. Travel time picks from 74 NTS nuclear tests recorded at regional stations and analyzed by Ryall are shown. Top plot (a) shows picks and linear travel time fits after removing three sigma outliers. Bottom plot (b) shows an expanded view of the reduced Pn picks listed by station along with the total number of Pn picks available. Some obvious outliers due to clock problems are labeled by the event names.

In Figure 3 we show 50 of the high quality subset events around the Nevada Test Site. The high level of natural earthquake activity since the 1992 Landers earthquake provides a nice dataset to contrast with the nuclear tests that ended in 1992. Recently a number of studies have been done that investigate the details of this seismicity (e.g. Smith et al, 2003; Ichinose, 2003). We use these studies to provide additional ground-truth about these events such as focal mechanisms and depth.

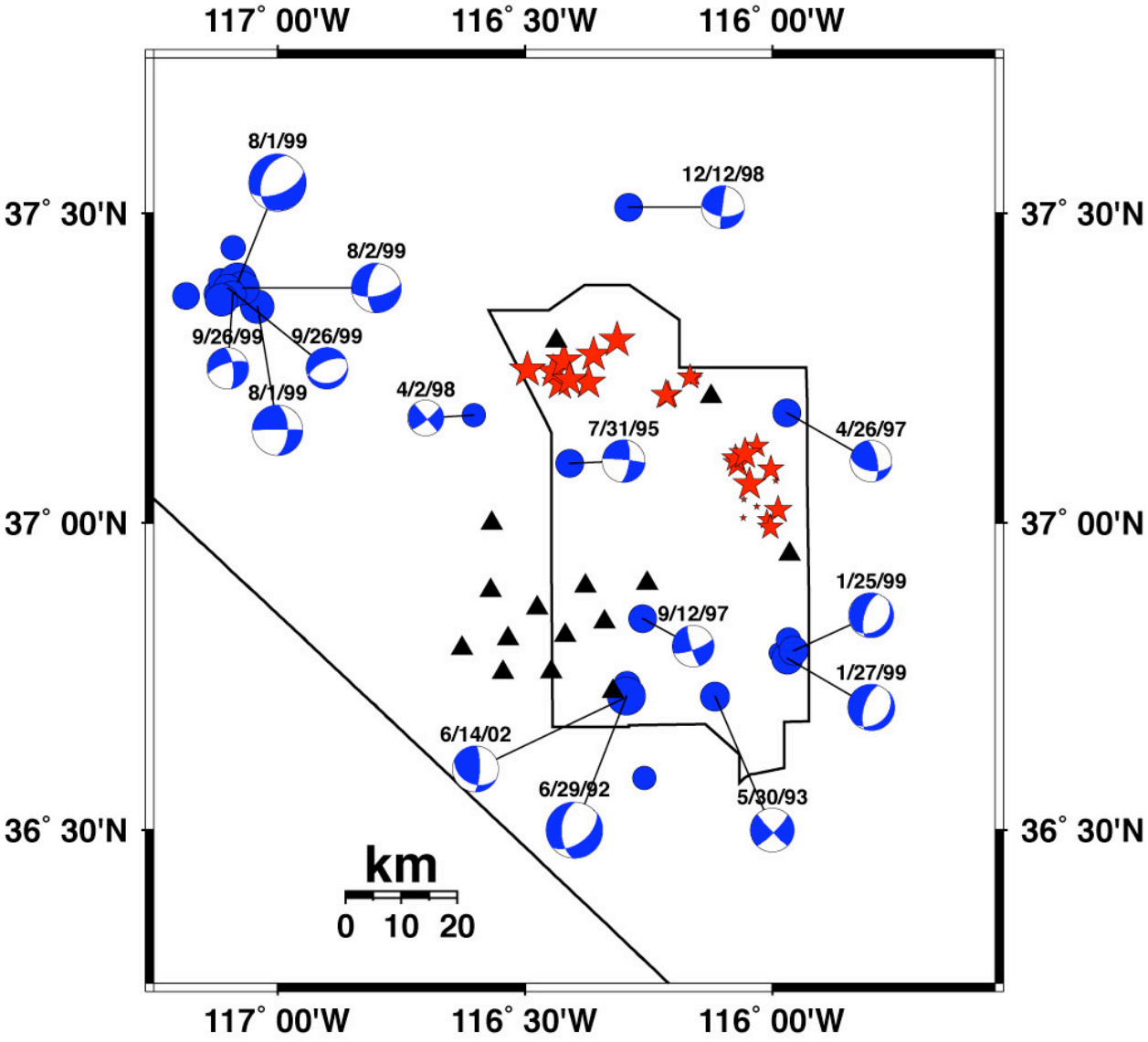

Figure 3. A map showing 25 earthquakes (blue circles) and 25 explosions (red stars) from 1989-2002 near NTS that are included in the high quality data subset. The map shows the boundaries of NTS and the locations of some of the UNR run Southern Great Basin network which can provide excellent ground truth hypocenter information for many of these events. Also shown are focal mechanisms for about 15 of these earthquakes drawn from regional studies by Smith et al (2002), Ichinose et al (2002) and the U.C. Berkeley moment tensor catalog. These earthquakes cover most of the seismicity in this region with magnitudes greater than about 3.5. The nuclear explosions cover the most recent 25 events when seismic network coverage is most complete and cover all three main testing areas at NTS (Pahute Mesa, Rainier Mesa and Yucca Flat). The explosions also cover a fairly full range of magnitude, depths and source material properties.

At the conclusion of this project we plan to put the high quality subset of approximately 125 events, along with associated parameters (time picks, focal mechanisms, source media properties, etc.) on a CD-ROM in Knowledge Base (KB) schema compatible database format for release to interested monitoring researchers. We hope this well-organized and compact set of data will prove useful in both researching and benchmarking seismic monitoring algorithms in detection, location, identification and magnitude yield estimation.

CONCLUSIONS AND RECOMMENDATIONS

We are finishing this ROA project to build the most complete and best-documented database of regional distance nuclear explosion, earthquake, and mine-related digital broadband seismograms in the western U.S. We have selected and marked phase onset times for a high quality subset of this data, which will be distributed at the conclusion of this project. We believe this set of consistently picked, independently located data will provide an effective test set for regional sparse station location algorithms. In addition because the set will include nuclear tests, earthquakes, and mine-related events, each with related source parameters, it will provide a valuable test set for regional discrimination and magnitude/yield estimation as well.

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